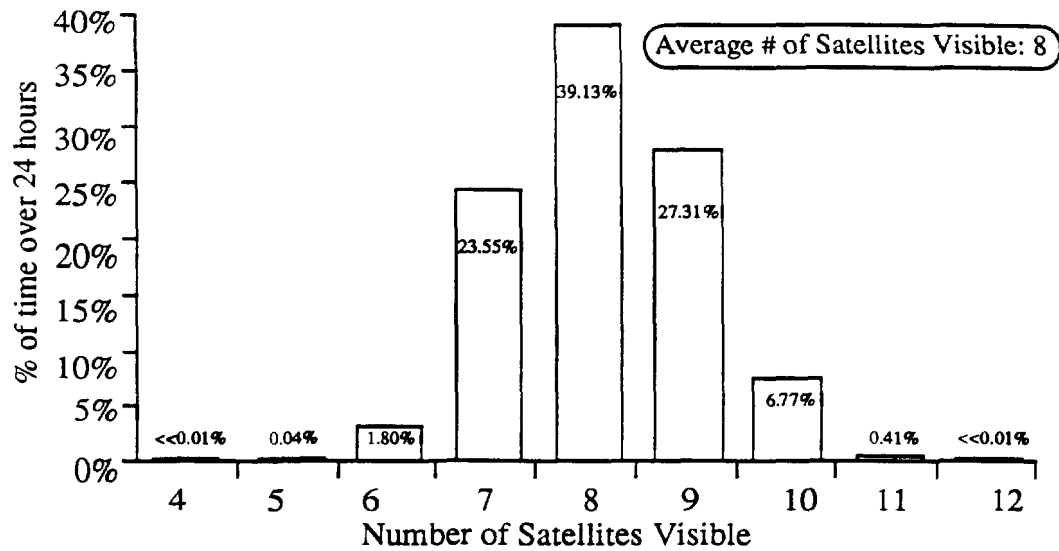
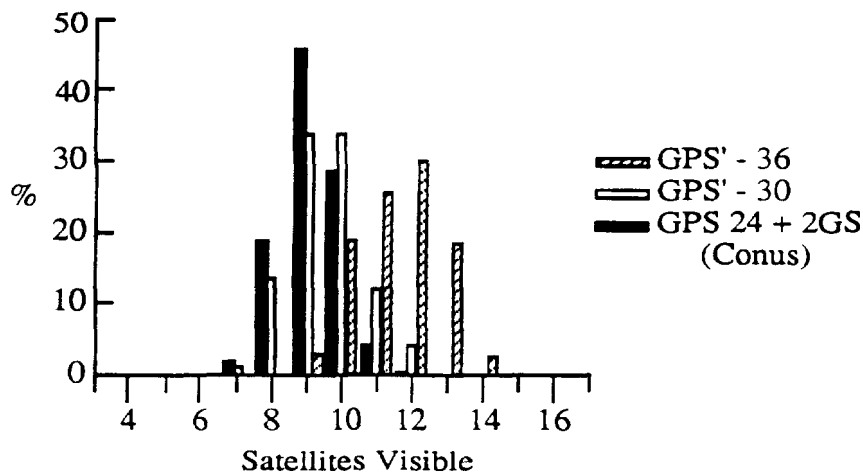


**Exhibit 4-3.
Availability and Visibility of HDOP
vs. Constellation Size**



4-3A. Satellite Global Visibility Profile



4-3B. Availability vs. Constellation Size

Reference: P. Misra et al., op. cit.

are roughly equivalent to 6 additional GPS spacecraft (a ratio of 1:3). Qualitatively, this can be seen to be reasonable since each GPS spacecraft contributes roughly 8 hours of visibility (at a given ground site) per 24, while a GS contributes a full 24 hours of visibility.

Misra, et al.⁴, extended the results of Exhibit 4-3 by considering the integrity level that could be "protected" with candidate algorithms for Receiver Autonomous Integrity Monitoring (RAIM). The results are illustrated in Exhibit 4-4. Again, note the close similarity between the GPS24+2GS constellation and the hypothetical GPS-30 constellation. For these constellations, an integrity protection limit of roughly 500 meters could be satisfied roughly 99.9% of the time. Note that, for this analysis, the GS relays in the GPS24+2GS constellation provide ranging signals, but no ground-based integrity data or differential corrections.

TSO'd GNSS receivers will be aided by barometric data; the number of independent measurements available for RAIM and Fault Detection/Isolation (FDI) is therefore one greater than the number of spacecraft visible at any given time. Reinterpreting Exhibit 4-3 in light of barometric aiding and a downward adjustment in mask angle to 5 degrees, we conclude that either a GPS24+2GS+baro system (as is contemplated for domestic US airspace), or a minimum of 30 GPS spacecraft + baro, would yield a minimum of 8 measurements at any time exclusive of satellite failures. It seems likely that the curves in Exhibit 4-4 would also be "lifted" by about one "9", although this contention should be validated with actual analysis.

The data in Exhibit 4-1 accounted for expected failure rates in the GPS and GS constellations, but the data in Exhibits 4-3 and 4-4 assume perfect health by all satellites. As a result, these data are optimistic to an unknown degree. Refinement to include expected failure rates would require extensive Monte Carlo simulation runs designed to capture a representative sampling of the most likely failure modes.

Exhibit 4-5 illustrates typical visibility and HDOP performance, again from Misra, et al., for GPS+GLONASS assuming three random satellite failures in each constellation (a total of six failures). GPS-only data is provided for comparison. The dual constellation exhibits substantial capability even after accounting for random failures. A minimum of 9 satellites are always visible. This represents a lower bound on performance for several reasons. First, the basic assumption of 3 satellite failures in each constellation puts these data at the "tail" of the probability distribution. As indicated previously in Exhibit 4-2, the GPS constellation alone expects to have 2 failures or less 98% of the time. Furthermore, Exhibit 4-5 assumes a user mask angle of 7.5 degrees, and no benefit from barometric aiding. Nevertheless, these data provide a starting point for analysis.

In terms of signal tracking capability, the following assumptions are applied based on the results of Section 3, unless stated otherwise:

1. Nominally, GPS and GLONASS signal tracking is not affected by MES operations at 100m.
2. At a range of 100m, the estimated probability of operation at J/S ratios greater than ARINC 743A-1 specifications is 2.5×10^{-6} for GPS.
3. At a range of 100m, the estimated probability of operation at J/S ratios greater than ARINC 743A-1 specifications is 2×10^{-3} for GLONASS (antipodal frequency plan 1-12 is assumed for the timeframe of Globalstar operations).

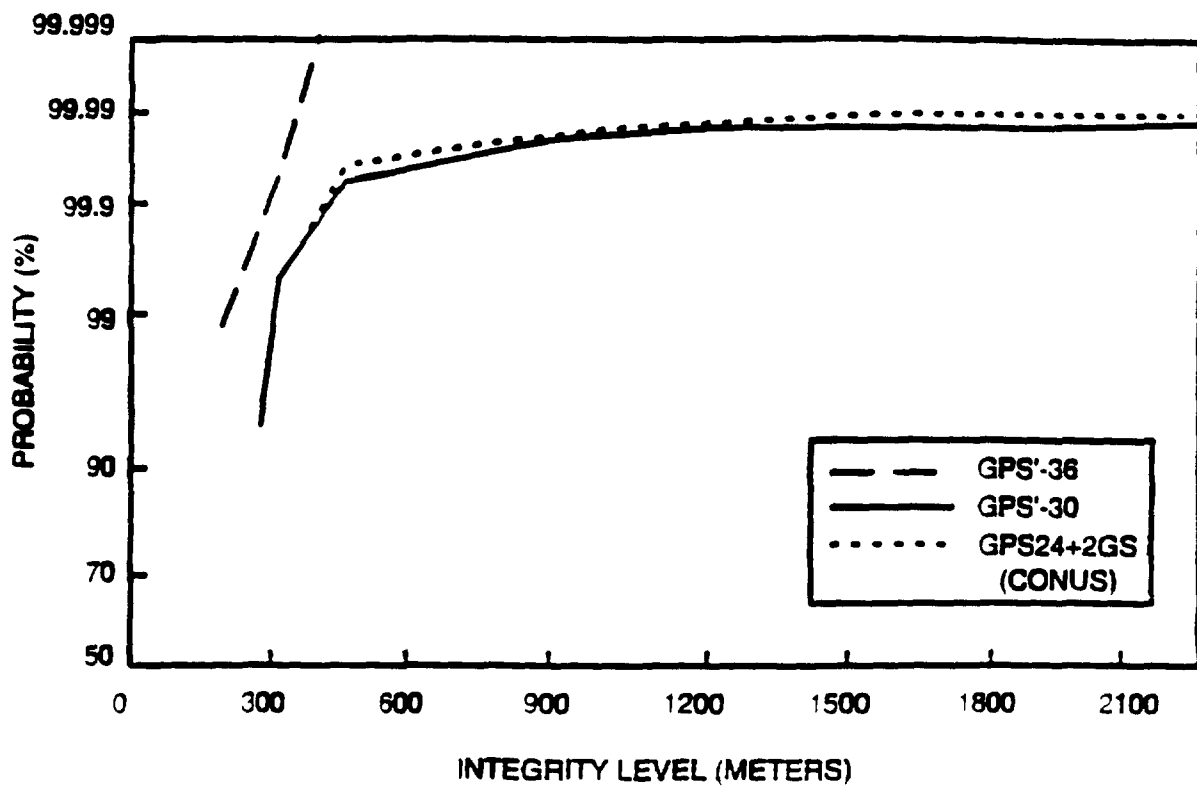
With this background on typical GNSS performance, it is now possible to address specific phases of flight.

4. P. Misra, et. al., *Receiver Autonomous Integrity Monitoring (RAIM) of GPS and GLONASS, Navigation*, Spring 1993.

Exhibit 4-4.

Availability of GNSS Navigation with Integrity (SA on)

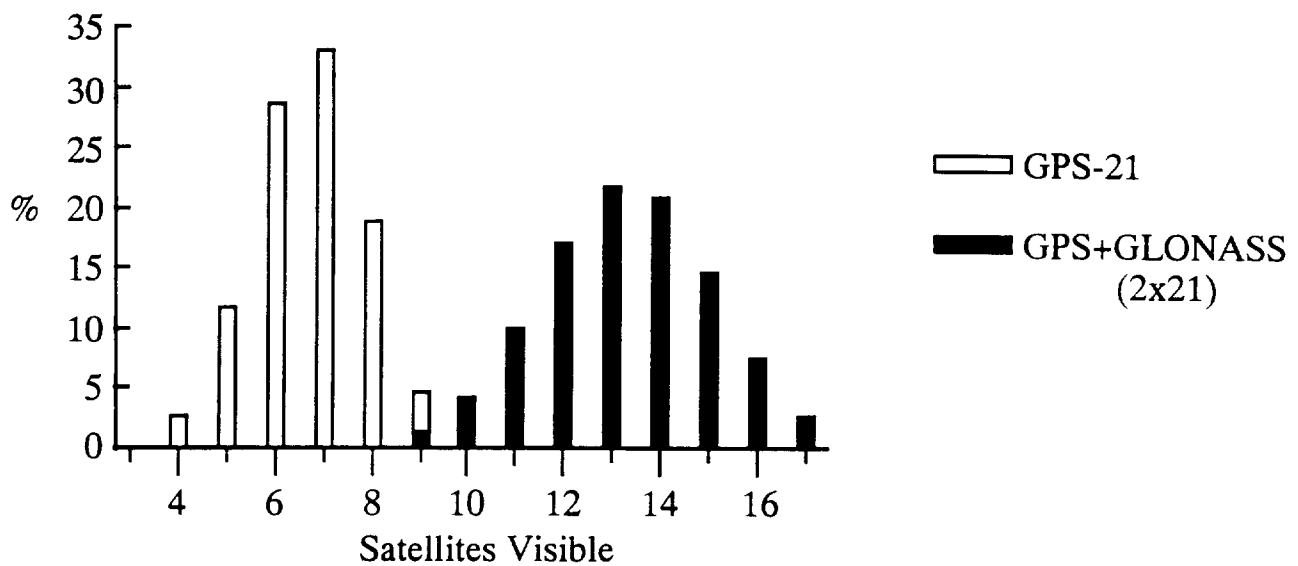
Integrity Level (meters) with SA



Reference: P. Misra et al., op. cit.

Exhibit 4-5

Satellite Visibility Statistics for GPS and GLONASS



Reference: P. Misra, et al., op. cit.

Exhibit 4-6

OUTAGE TIME CALCULATION FOR GNSS RCVR AFFECTED BY GLOBALSTAR MES

ASSUMPTIONS:

1. Direct overhead pass
2. GNSS signals at minimum specified levels
3. GPS signal tracking lost at average C/I = -24 dB
4. No MES signal blockage by airframe

$d = -0$ d is the MES duty cycle in dB
 $Noise = -20.5$ Maximum RFI power level in dBm for shadowed operation
 $Dir_gain = -5$ Directive gain of GNSS antenna toward MES
 $EIRP = Noise + d$ EIRP is expressed in dBm
 $Velocity = 33.36$ Aircraft ground speed in meters/sec (100km/hr = 27.8 m/s)
 $height = 25, 50, 300$ Aircraft height above terrain

$$Req_space_loss = -106 - EIRP - Dir_gain$$

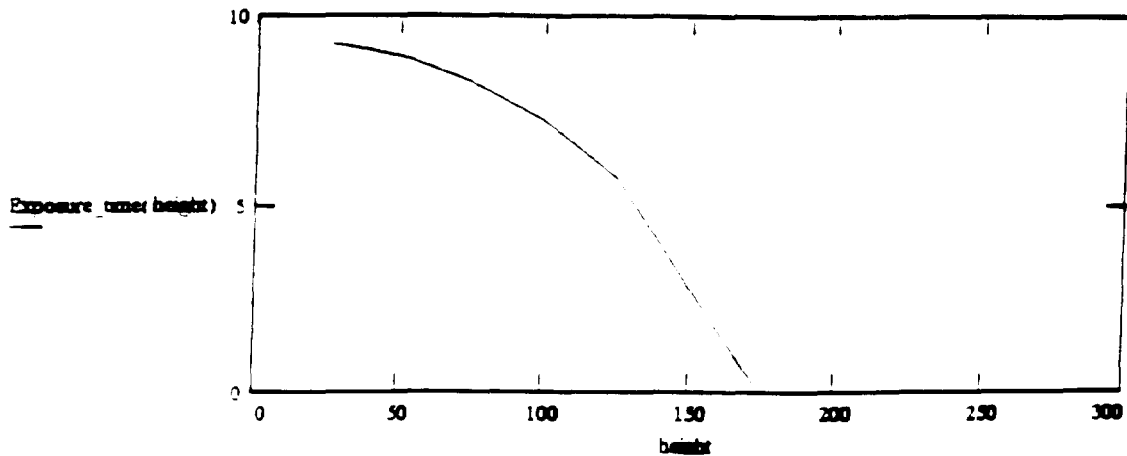
$$Req_space_loss = -80.5$$

$$Threat_radius = 10^{\left(\log\left(\frac{0.186339}{4-\pi} \right) - \frac{Req_space_loss}{20} \right)}$$

$$Threat_radius = 157.067$$

$$Exposure_distance(height) = 2 \cdot \sqrt{(Threat_radius^2) - height^2}$$

$$Exposure_time(height) = \frac{Exposure_distance(height)}{Velocity}$$



4.2 En Route and Terminal Area Operations

Sole means navigation in the en route and terminal area airspace requires a navigation system that can deliver fault-free 95% accuracy of 0.124 nmi (horizontally), with integrity, at availability levels of 0.99999. In US airspace, GNSS equipment must include altimeter aiding to enhance availability with integrity. Nevertheless, GPS plus altitude input alone is insufficient to achieve sole means performance. R. Grover Brown, et. al.⁵, determined that, for one candidate integrity assurance algorithm, availability with fault detection capability within the United States would be about 99.9% for terminal area operations. Availability with fault detection and isolation (implying a "fail-operational" capability) was only 94.3% for terminal area operations.

To achieve availability levels of 0.99999, augmentation with GLONASS or geosynchronous satellites is required. In the US, the FAA is energetically pursuing development and deployment of a WAAS in order to support primary means navigation. This system will nominally provide at least double coverage by geosynchronous spacecraft everywhere in the continental US. As noted above, Misra, et. al.,⁶ determined through numerous simulations that two visible geosynchronous satellites are sufficient (barely) to satisfy sole means requirements on availability and integrity (These analyses assumed a mask angle of 7.5 degrees, no integrity broadcast and no differential corrections through the GS's, and no use of barometric aiding. Current FAA and aviation industry planning would imply substantially better performance).

On the other hand, Misra's analysis ignored the effects of satellite failures for the cases reported above. This will offset, to some modest extent (TBD), the performance gains associated with lower mask angle, integrity and possibly DGPS corrections, and baro aiding. An overlay of two geosynchronous spacecraft was also found to be roughly equivalent, from a RAIM standpoint, to six additional GPS spacecraft. This rough correspondence can be used to assess the impact of losing some portion of the GLONASS constellation due to RFI.

What is the operational impact of RFI on a GPS+WAAS or GPS+GLONASS system? As indicated earlier in Section 3, nominal operations by an MES will not degrade GPS operations (or WAAS operations, which are on the same frequency) at a range of 100m. With full-power operations by the MES (i.e., during shadowed mode operations), GPS or GPS + WAAS operations have a small chance of encountering J/S ratios that exceed 24 dB. This probability is approximately 2.5×10^{-6} (for MES noise floor 59 dB down from inband signal) or 6.5×10^{-4} (for MES noise floor 54 dB down). An exposure time can be calculated for the latter case based on the nominal link budget parameters and full power MES operations. This calculation is presented in exhibit 4-6 assuming an aircraft is actually operating at an altitude of 100m, and that it passes directly over an MES operating in a shadowed mode (but the shadowing does not reduce the flux density impinging on the aircraft), and assuming a relatively slow ground speed of 33 meters/second (75mph), and taking no credit for airframe blockage/shielding (despite the earlier assumption of a perfect overhead pass). The period of degradation would not exceed 7 seconds. This is shorter than the alarm time constraint of 30 seconds for terminal area operations, indicating no operational impact even for this highly contrived and unrealistic case.

5. R. Grover Brown, et. al., **Assessment of RAIM FDI Availability Using ARP Method of Screening Out Bad Geometries**, US Department of Transportation, Volpe Center, Cambridge MA. RTCA paper No. 213-93/SC159-436, May 1993.

6. P. Misra, et. al., **Receiver Autonomous Integrity Monitoring (RAIM) of GPS and GLONASS**, *Navigation*, Spring 1993.

For an MES noise floor 59 dB down from the inband signal, a deterministic calculation of exposure time yields 0 seconds exposure since the nominal link budget provides positive margin even with full power operations. In either case, it should be emphasized that it is unlikely an aircraft would operate that close to the ground for normal en route or terminal area operations. Flight below 500 feet (152m) is disallowed in populated areas, so a 100m separation between an aircraft and an MES would have to be accidental. By comparison, the Minimum Descent Altitude during non-precision approach is 250 feet above terrain, or 76m. A 100m vertical separation would place the aircraft in the final stages of an approach, as opposed to en route or terminal area operations.

For GPS+GLONASS, a slow low-altitude pass directly over an MES could potentially degrade signal tracking in some GLONASS channels. The probability is dependent on both MES and GLONASS channel ID, and varies from approximately 6.5×10^{-4} to 1.0 (for some combinations involving GLONASS channels 22, 23, and 24). The average probability of degraded signal tracking for the near-term antipodal scheme, is approximately 0.3%. Again, it should be emphasized that this scenario assumes an accidental (nominally illegal) low-altitude pass.

4.3 Non Precision Approach Operations

The FAA has already certified GPS with barometric altimeter aiding for supplemental use and planned sole means use down to NPA minima. The GPS+WAAS will satisfy sole means requirements down to this level as well. If high-accuracy differential corrections are available through the WAAS, GPS+WAAS will actually support Category I precision approach, although the projected availability may be closer to 0.999. Prior availability studies by numerous investigators supports the conclusion that GPS+2 or 3 geosynchronous spacecraft will support NPA requirements.

As one example, Exhibit 4-7 illustrates summary data generated by Phlong and Elrod. Both the accuracy and integrity protection limits are satisfied by 2 GS and 3 GS augmentations to GPS, for the pseudorange errors mandated for the system. For this analysis, the geosynchronous spacecraft were treated as sources of ranging data only; all GPS and GS spacecraft were also subjected to failure rate statistics consistent with historical data, and barometric aiding was neglected.

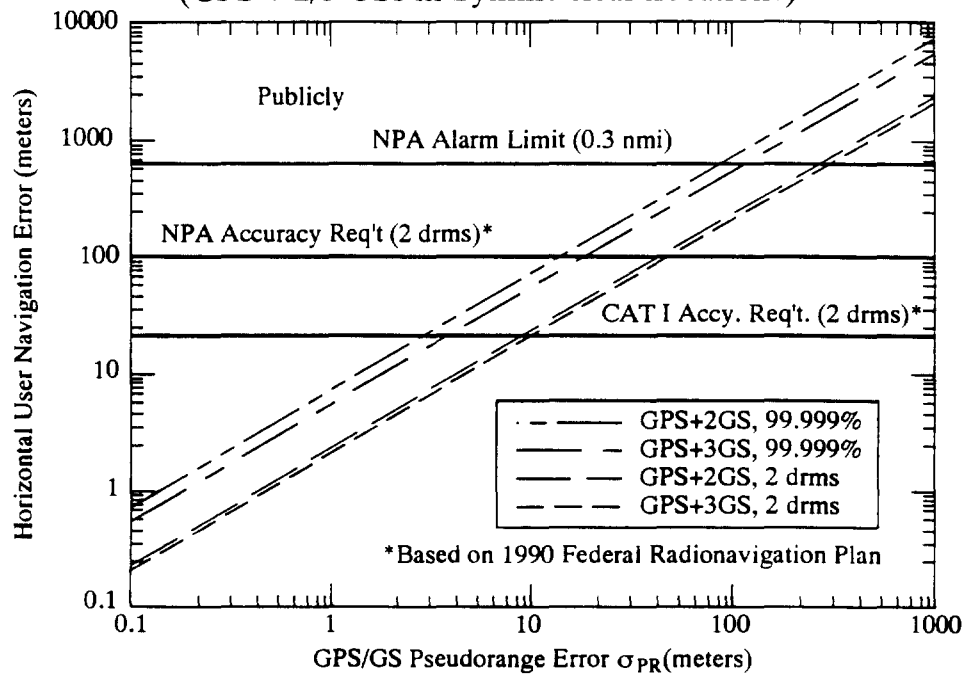
Since the performance impact of each additional GS is essentially equivalent to three additional GPS spacecraft (or a somewhat greater number of GLONASS spacecraft), we can conclude that NPA operations are satisfied under nominal conditions with GPS plus roughly one quarter to one half of the GLONASS constellation.

One potential issue for a GPS+GLONASS system supporting NPA operations is Continuity of Service. The NPA requirement for Continuity of Service is in flux, and could be as low as 0.9999 or as stringent as $(1-10^{-8})/\text{hour}$. As indicated previously by Exhibit 4-6, high power MES emissions have the potential to degrade GNSS receiver tracking performance for a short period of time. The probability of this event depends on the MES transmitter's far out-of-band noise floor (whether it is 54 dB or 59 dB down from the inband signal), and whether the GNSS signal is from GPS or GLONASS. Relevant probabilities are tabulated in Exhibit 4-8, under conservative assumptions, at a range of 100m. Note that the lower noise floor leads to a probability of 2.5×10^{-6} for GPS, although the deterministic analysis of Exhibit 3-1 indicated positive margin even with full power MES operations. This would appear to meet NPA requirements for Continuity of Service for users relying on GPS + WAAS + baro, although it will be necessary to verify this fact when the WAAS specification is finalized (note that the event probability of 2.5×10^{-6} is conditioned on the presence of an MES directly under the flight path for the approach, as well as the fact that the MES is in use, and that the user is keying the microphone at

the instant of the overhead pass. These are probabilistic conditions in themselves, which would tend to further reduce the risk of J/S ratio exceedence. In any case, given that NPA is considered to be a less stressing operation than Category I precision approach, it is likely that the Continuity requirement for NPA will be no worse than the Continuity requirement already defined for Special Category I precision approach, which is 6×10^{-5} per approach).

In the case of a user relying on GPS + GLONASS, average probabilities of J/S exceedence are higher due to the higher noise floor perceived by GLONASS, as well as the possibility that the MES channel will be close enough to a GLONASS channel to inject a portion of the intermodulation skirt into the GNSS receiver. However, as indicated in Exhibit 3-6, even in the case of the GLONASS near-term antipodal scheme, eight of the twelve frequency channels have probabilities of signal exceedence $\leq 7 \times 10^{-4}$. When combined with a) the low probability of occurrence, b) the conservative assumptions, c) the large number of visible spacecraft in this scenario, and d) the potential for continued signal tracking and acceptable navigation performance, even in the event of J/S threshold exceedence, it seems reasonable to conclude that the potential for signal tracking impairment is not operationally significant for NPA. Furthermore, TSO C-129 allows coasting of RAIM for up to five minutes as long as a pre-approach integrity check was performed, and the navigation function is preserved. Thus, as long as GPS+baro can provide a navigation solution, the chance of losing integrity due to GLONASS signal tracking is acceptable. Young Lee has shown that GPS+baro provides essentially 100% availability of navigation, even with up to three failures in the GPS constellation. This indicates that MES emissions have no operational impact on NPA operations. Nevertheless, further analysis may be warranted to refine the availability statistics for GPS+baro, as well as the link budget assumptions and analyses. It may be necessary to extend the results to eight significant digits, in order to demonstrate no operational impact relative to the potential NPA Continuity of Service specification of $(1-10^{-8}/\text{hr})$.

Exhibit 4-7: Horizontal User Navigation Performance
(GPS + 2/3 GSs in Symmetrical Locations)



ref.: Phlong and Elrod, "Availability Characteristics of GPS and Augmentation," ION National Technical Meeting, January 1993

Exhibit 4-8: Probability of J/S Exceedance at 100m

Spacecraft and Frequency Plan	MES Noise Floor (dBc)	
	-59	-54
GPS	2.5×10^{-6}	6.5×10^{-4}
GLONASS (-6, 6)	N/A	6.5×10^{-4}
GLONASS (1, 12)	N/A	0.003

4.4 Category I Precision Approach Operations

Category I precision approach operations absolutely require some form of differential overlay, such as the WAAS or a local area differential system. A WAAS or local-area differential system is a necessary and sufficient augmentation to GPS to satisfy Category I approach requirements. GLONASS may be employed as an adjunct to enhance availability, but is not required. Thus, from an availability standpoint, complete loss of GLONASS can be tolerated without incurring a significant operational penalty. On the other hand, as with NPA, continuity of service is a key parameter of required navigation performance in precision approach operations. Continuity of service is important because a loss of navigation service could force the pilot to execute a missed approach, and there is a small but nonzero safety risk associated with missed approach operations.

The Special Category I requirement for Continuity of Service is 6×10^{-5} over the duration of an approach (i.e., Final Approach Fix down to the 200 foot decision height). The probability of impairment is less than or equal to the probability of J/S exceedance, which is 2.5×10^{-6} for an MES noise floor 59 dB down from the inband signal. This would be acceptable compared to the 6×10^{-5} required. Further analysis may be warranted with respect to the higher noise floor alternative.

A continuity problem could also arise if a pilot begins an approach under a degraded GPS constellation, where the pilot relies on GLONASS to provide the necessary minimum number of ranging signals or geometry, and these signals become degraded during the approach due to RFI. (Note: in this scenario, GPS signal processing is unaffected, but GPS alone is insufficient to support the approach). In this situation, significant signal degradation could lead the avionics to declare an integrity alarm; the pilot would be forced to execute a missed approach if the alarm occurred before the pilot visually acquired the runway. Further analysis should be performed to assess the potential for signal tracking degradation, as well as the probability of impairment to the user's navigation function. If further analysis shows that navigation or integrity functionality can be degraded, one of the following response strategies could be adopted:

- a. **Take availability penalty on GPS+GLONASS receivers.** Under this strategy, users with GPS+GLONASS receivers would limit their precision approach operations to those times and places where GLONASS was not required (i.e., the precision approach operation could be projected to completion based solely on the currently-available GPS spacecraft, barometric aiding and possible GS augmentations). The impact of this strategy on actual or calculated availability is TBD.
- b. **Assume average constellation performance.** Under this strategy, one would argue that the vast majority of all approaches can be completed without GLONASS; therefore, an occasional missed approach due to loss of selected satellites is tolerable (it is no different from missed approaches due to poor flight technical error, bad weather, etc.). This strategy applies the Continuity requirement to the aggregate of all approaches rather than each approach individually. The policy impact of this strategy is TBD.
- c. **Limit Globalstar MES emissions in the vicinity of airports supporting precision approach operations.** Under this strategy, MES's operating in beams that contain airports supporting GNSS-based precision approach operations would not be commanded to power levels that could impair GLONASS operations. The impact on Globalstar perceived quality of service is TBD.
- d. **Limit Globalstar MES emissions by more elaborate out-of-band filtering.** Under this strategy, MES electronics would be augmented to provide additional isolation in the GNSS band. The impact on Globalstar MES costs is TBD.

4.5 Surface Operations

As with precision approach, surface operations absolutely require some form of differential overlay such as the WAAS or a local area differential system. A WAAS or local-area differential system is a necessary and sufficient augmentation to satisfy surface operation requirements -- especially accuracy. Integrity is provided by the differential overlay, and theoretical availability is at least an order of magnitude higher than in the terminal area because surface operations are inherently 2-dimensional (they require one less satellite assuming the GNSS receiver has pre-determined airport altitude, or has read this data from an on-board data base). GLONASS may be employed as an adjunct to enhance availability even more, but is not required. Thus, from an availability standpoint, complete loss of GLONASS can be tolerated without incurring an operational penalty.

Current airport operations do not generally depend on electronic nav aids for surface navigation. Future operations may involve some fraction of the high-end air fleet acquiring this capability, but it is not likely to become required equipment in the foreseeable future. The availability of GNSS-based navigation for surface operations is essentially a cost/benefit issue rather than a safety of flight issue. The existence of GNSS may enhance traffic management efficiency on the airport surface in the future. If GNSS becomes an integral part of future surface navigation and traffic management systems, its absence or loss could degrade traffic management efficiency. It may also result in selected aircraft being forced to stop, and cease operations. On the other hand, as long as the pilots heed the directions of the ground controllers, safety will be maintained. Given a) the lack of defined availability standards for surface navigation, b) the lack of safety concerns, c) the exceptionally high availability of surface navigation even without GLONASS, and d) the general robustness of GPS signal processing relative to expected MES emission levels, there appears to be no significant issue or serious concern in the surface domain.

Section 5

Summary and Conclusions

5.1 Summary

An assessment of Globalstar MES emissions on GNSS receiver navigation performance has been performed. This assessment focused on the operational impact of MES emissions on user navigation performance relative to generally accepted standards of Required Navigation Performance (RNP) as a function of user phase of flight. Analytic refinement is possible and desirable in many areas:

1. **The definition of RNP is evolving.** Internationally, the ICAO RGCSP (Review of the General Concept of Separation Panel) and AWOP (All Weather Operations Panel) is attempting to forge a broad consensus on the definition of RNP. Domestically, the FAA is initiating an effort to redefine the basic requirements documents for the National Airspace System in terms of RNP. The precise definition of RNP and threshold levels for each phase of flight are being refined through analysis and consensus.
2. **MES operating characteristics are projections.** The characteristics assumed here are subject to refinement.
3. **GNSS receiver operating characteristics and performance requirements should be improved.** The prior requirements were driven by formal specifications, which have tended to ignore advancements in technology and normal engineering margins. In particular, the analysis reported here assumes that navigation performance could be lost at J/S ratios that marginally exceed the ARINC Characteristic 743A-1 specifications. Therefore, upgraded specifications which would improve MSS sharing is required as discussed by ARINC at the NRM.
4. **GNSS constellation expected performance levels are projections.** As operational confidence in GNSS builds over time, and as historical experience dictates, assumed failure rates will be adjusted. Further analysis is also required to extend currently available performance data, which were derived from assumptions that do not precisely match projected GNSS operations scenarios or evolving certification requirements.
5. **Future GNSS receivers may incorporate enhanced signal rejection technologies.** The specifications for GNSS receivers that will operate in conjunction with WAAS, and provide primary means navigation capability via GNSS, are currently being developed. Interference assessment analyses are ongoing in the aviation community, and RFI mitigation techniques are being evaluated with an eye toward enhancing GNSS receiver robustness. These mitigations include filtering, revisions in the A/D circuitry and other changes.

In spite of these influences, an initial worst case MES impact assessment has been completed. The US requirement for barometric aiding (via TSO C-129) significantly improves the expected level of performance of the most disadvantaged user in US airspace. From a visibility standpoint, a full GPS constellation with two additional geosynchronous spacecraft is sufficient to satisfy all accuracy, availability and integrity requirements in all phases of flight except precision approach. If differential corrections are available through the geosynchronous spacecraft, Category I precision approach requirements can be satisfied as well. Similar performance can be achieved with a full GPS constellation and six additional satellites operated in coordination with GPS.

The expected incidence of satellite failures and short-term outages (e.g., due to maneuvers) will increase the requirements. However, reliability studies indicate that only small increases in the number of visible satellites will be required. These studies need to be refined and extended with a specific focus on GLONASS, lower mask angles (5 degrees) and barometric aiding. Nevertheless, data available to date indicate that acceptable performance can be maintained with GPS plus one-fourth to one-half of the GLONASS constellation.

In US airspace, it is important to recognize that certificated GNSS receivers will incorporate barometric aiding, and will have additional ranging signals (and integrity information) from typically two additional geosynchronous spacecraft in the timeframe of Globalstar operations. The impact of ground-derived integrity data on system performance was not included in the analysis, but would be expected to significantly improve performance and reduce constellation requirements.

From an availability standpoint, there is no requirement to track GLONASS satellites operating on channel assignments above 1606 MHz. The current GLONASS frequency plan would provide a minimum of six spacecraft operating on channels containing the C/A code below 1606 MHz. With antipodal assignments, GLONASS would offer an availability benefit of 12 operating spacecraft which is equivalent to approximately 4 geosynchronous spacecraft. However, as little as two geosynchronous spacecraft were shown previously (in Section 4) to satisfy primary means availability requirements in all phases of flight, as well as accuracy, availability, integrity and continuity requirements for en route, terminal area and NPA operations. (Note: Category I precision approach and surface operations require a differential overlay to enhance accuracy, and Category I precision approach also requires a differential overlay to enhance integrity. A WAAS would also provide additional ranging signals to enhance availability further.)

5.2 Conclusions

The conclusion of the MES impact assessment is that a Continuity concern might exist (depending on the final status of evolving requirements) for NPA and Category I Precision Approach operations under the assumption of a far out-of-band noise floor that is only 54 dB below the desired signal. However, for a far out-of-band noise floor that is 59 dB below the desired signal, there is no operational impact in en route airspace, terminal area airspace, nonprecision approach and for surface operations. For Category I precision approach, there is no impact for users that rely on GPS+WAAS (+baro). Continuity of service may be affected under a conservative set of analytic ground rules in cases where a GNSS user relies on GLONASS during the approach to provide needed additional integrity assurance for safe operations. This is not a likely mode of operation in the United States, although it may exist elsewhere. Furthermore, within the United States and adjacent regions, augmentations such as the WAAS are planned to be sufficient to support primary means navigation down to Category I minima without reliance on GLONASS.

For users who choose to depend on GLONASS in lieu of, or in addition to the WAAS, a potential interference mode exists. For these users, the presence of an active MES close to the extended runway centerline in a narrow region approximately 0.75 miles from runway threshold, operating in a shadowed mode (resulting in a high power MES transmission), could lead to a loss of GLONASS signal tracking and therefore loss of navigation system integrity, although navigation guidance is not lost at this point, or even necessarily degraded. In this situation, the user's avionics would potentially declare an integrity alarm that could lead to a missed approach.

Whether an integrity alarm is actually declared depends on numerous real-time parameters as well as the possible use of alternative nav aids such as inertial reference systems, etc. We emphasize that almost any change in the underlying assumptions for this scenario would eliminate the possibility of signal tracking degradation. These changes include: (1) reliance on the WAAS; (2) reliance on WAAS ranging signals and on local DGPS correction and integrity broadcast;

(3) less than full-power MES operations; (4) GNSS antenna directive gain less than -5 dBi toward the MES; (5) airframe or environmental shielding; (6) GNSS signals above minimum specified received power levels; or (7) GNSS receiver performance that exceeds the conservative ARINC 743A-1 J/S specifications.

Further analysis of continuity of service is recommended, with a specific focus on hybrid constellations including GLONASS and GLONASS with WAAS, as well as the use of a mask angle of five degrees, and barometric aiding. This work can be performed on a theoretical basis with data currently available in the engineering community. Further refinement of the RFI link budgets would also be desirable, with specific focus on estimating GNSS antenna patterns below the horizontal and potential airframe shielding/shadowing parameters (if these can be measured or estimated).

Refinement of MES operating protocols would also be desirable, as would an assessment of actual signal tracking mechanisms within typical GNSS receivers. These assessments, taken together, should completely resolve all remaining concerns, and demonstrate that MES operations are not operationally significant to GNSS receivers operating at ranges of 100m or greater.

Assessment of MES-Induced RFI on Hybrid GPS/GLONASS Aviation Receivers

References

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5. Misra, P. et al., **Receiver Autonomous Integrity Monitoring (RAIM) of GPS and GLONASS**. *Navigation*, Journal of the ION, pps. 87-104. Institute of Navigation, Alexandria, VA. Vol. 40, No. 1, Spring 1993.
6. Phlong, W.S. and B.D. Elrod, **Availability Characteristics of GPS and Augmentation Alternatives**. *Proceedings of the ION National Technical Meeting*, pps. 69-80, The Institute of Navigation, Alexandria, VA. January 1993.

Appendix A

Analytic Modifications Assuming Independent GPS And GLONASS Navigation Solutions

The body of this report assumed that all available pseudoranges were fused into a single navigation solution, with extra measurements (degrees of freedom) used to provide integrity in the form of fault detection and isolation. If separate navigation solutions are generated and compared "after the fact", overall operational availability will be degraded because a minimum of four satellites with good geometry are required from each constellation. With exactly four satellites from each constellation (i.e., eight signals total), a comparative algorithm can detect the presence of a problem, but cannot isolate it. The equivalent capability can be supported with a total of only five signals, in any mixture of GPS and GLONASS (in good geometry), with a fused algorithm. Similarly, fault detection and isolation requires a minimum of five satellites with good geometry from each constellation with a comparative algorithm, but only 6 satellites with good geometry for a fused algorithm.

The overall performance of comparative algorithms has not been investigated extensively by the aviation or navigation industry; however, preliminary assessments can be generated by interpreting the data for single constellations relative to their ability to support navigation with fault detection. If both constellations provide the ability to navigate with fault detection, the combination of the two will provide navigation with fault detection and isolation. This is true because a single failure can be detected in either constellation, and the remaining constellation is known (at that time) to be fault-free.

Young Lee³ estimated that GPS+baro would provide an availability typically between 70% and 90% for navigation with fault detection, at five major airports distributed throughout CONUS. This estimate was for a navigation protection limit of 0.3 nmi (nonprecision approach), user mask angle of 7.5 degrees, and 21 operational satellites out of a 24 GPS constellation. The equivalent availability for terminal area operations was estimated at between 90% and 93%. If these results are assumed to hold for GLONASS as well, and the two constellations are assumed independent, then a comparative algorithm would yield availabilities of between 90% and 99% (roughly) for navigation with fault detection and isolation in terminal area and NPA operations. These availabilities do not satisfy primary means RNP. Thus, a comparative algorithm is not a viable alternative for GNSS receivers in the absence of other augmentations (such as WAAS).

RF interference modes will be insignificant from an availability and continuity standpoint for en route and terminal area operations (i.e., they will have an insignificant additional impact on availability). In these phases of flight, an aviation user should be outside even the conservative threat region around an MES. As noted previously, an aircraft should not be flying below 500 feet (152m.) above terrain in populated areas. Even if an aircraft is actually flying this low, and passes directly over an MES operating at full power, exposure times for both GPS and GLONASS are less than the time to alarm in these domains, indicating robust performance.

As with a fusion-type algorithm, RF interference modes can potentially affect Continuity of Service for NPA (note that availability would be assessed at the beginning of the approach, which is at sufficient altitude to preclude any effect from a ground-based MES). When RF interference is considered, performance levels for continuity will be driven toward the values calculated in

1. Y. Lee, **RAIM Availability for GPS Augmented with Barometric Altimeter Aiding and Clock Coasting**, *Navigation, Journal of The Institute of Navigation*, Summer 1993.

Section 4. This is because the estimates in Section 4 made the conservative assumption to treat the entire GLONASS constellation as either available or not available. This is equivalent to degrading unexpectedly to an all-GPS environment in a comparison-type algorithm.

For precision approach operations, some differential overlay is absolutely required. As with NPA, a continuity impact may exist under very conservative assumptions. If so, the effect would be equivalent to that discussed in Section 4.

For surface operations, RNP is currently undefined. Nevertheless, given the 2-dimensional nature of the problem, the necessity for a differential overlay, and the lack of safety concerns, no operational impact is foreseen.

Appendix B

Impact of a Bad Upload

Both GPS and GLONASS have experienced during their developmental phases so-called "bad uploads", in which the navigation data uploaded to the spacecraft for subsequent downlink to the users are incorrect. In the absence of a differential overlay, such a situation may render the affected spacecraft unusable. Even with the planned differential overlay, nearly all of these upload error problems can be quickly detected and corrections provided to the users. However, if multiple spacecraft are affected, the constellation could become effectively unusable until the data are corrected. This is a serious concern, and both GPS and GLONASS take special precautions to prevent it from occurring. The incidence of such events can be expected to decline in the future for the operational constellations to an extremely small value, although some low probability of occurrence will always remain. This is one of the driving factors behind the need for a widely-available differential overlay that provides integrity, such as the WAAS.

If uploads (and subsequent navigation message switchovers) are managed such that mutually visible spacecraft do not switch their navigation messages simultaneously, a bad upload could be considered as only one additional cause of a short-term satellite outage. Given the very low probability of a bad upload, relative to other planned and unplanned short-term satellite outages, this formulation would imply a marginal impact on overall satellite availability statistics and resulting navigation performance. The conclusions presented earlier, for MES impact on GNSS operations, therefore would be unchanged.

If uploads are managed such that multiple mutually visible spacecraft are simultaneously affected, a potentially significant issue of navigation continuity and even integrity (under RAIM) may exist. This would be a serious matter for any GNSS user. This appears to be more of a GNSS operational control concern than a Globalstar MES concern.

Uploads should be managed in a non-simultaneous manner to the maximum extent possible, and continuing efforts are warranted to build in precautions against bad uploads, and to create rapid recovery procedures.

Appendix C

RFI Mitigation Techniques for GNSS Receivers

There are multiple sources of RFI potentially relevant to GNSS, and the aviation community is currently examining the overall RFI issue with the intent to review current standards for RFI mitigation. Technological solutions exist that would allow GNSS receivers to tolerate higher levels of RFI than implied by ARINC Characteristic 743A-1. Some of these may be incorporated in future standards for GNSS receivers intended to support sole-means navigation and approach/landing. Selected techniques are noted below. Their effectiveness for the particular forms of RFI generated by Globalstar MES operations will depend on the precise design of the MES, its operating regime, the relative geometry between the MES and the GNSS receiver, and the gain pattern of the GNSS antenna in the direction of the MES.

1. Adaptive filtering in the frequency domain. This technique would mitigate narrowband signals, narrowband intermodulation products and spurs in the GPS or GLONASS portions of the spectrum.
2. Increased emphasis on front-end linearity and dynamic range. In the presence of very strong RFI, virtually all communications and navigation receivers will eventually reach a condition where the front end operates nonlinearly. In this condition, signals are distorted and intermodulation products can develop inside the receiver. By focusing on improved linearity and dynamic range, future receivers could preserve the information contained in the received navigation signals at higher levels of RFI (relative to current equipment).
3. Blankers and limiters. These circuit elements are intended to mitigate very strong pulsed interference. Under normal operation, they are effectively transparent. However, with the onset of a very strong pulse of RFI, they will either limit the amount of energy passed to the subsequent circuit to a preset maximum level, or literally "blank" the signal for the duration of the pulse. In this way, the impact of strong pulsed RFI on circuit elements which integrate received energy is mitigated.
4. Vector tracking loop implementation. In all currently-available commercial GNSS receivers, each satellite signal is individually tracked in terms of its code state (group delay). Most receivers also track the carrier, to provide a more accurate and stable estimate of code state as well as relative velocity information (range-rate). Each tracking loop separately correlates to a single satellite signal (PRN code), treating all other signals as broadband noise. The tracking loops individually send information to the navigation filter, which merges the information into a single navigation solution. ARINC Characteristic 743A-1 specifies the J/S ratio for such a configuration, where the signal energy is that for a single satellite signal. An alternative configuration takes the tracking feedback from the navigation filter instead of the correlation process on a single signal -- error signals are still sent to the navigation filter as before, but the error signals are not "turned-around" on a per-channel basis for tracking. The effect of this change is to make the overall tracking process more robust by a multiplicative factor equal to the number of signals being tracked. For example, if five signals are being tracked (the minimum for navigation with fault detection), the tracking process would be 7 dB more robust than an equivalent circuit with individual tracking loops. If 10 signals are being tracked, the vector tracking loop would be 10 dB more robust than an equivalent implementation of single, or scalar, tracking loops. Surprisingly, the computational complexity of the vector tracking loop is no higher than the computational complexity of the standard implementation. However, the vector tracking loop may require a shorter cycle time through the navigation filter.

5. Adaptive antenna nulling. This technique relies on a more complex antenna with special processing to place a spatial null on received signals that do not appear to satisfy prespecified criteria. For example, an adaptive antenna could sense the signal power of all signals arriving from discrete directions, and null out the N largest signals that are not arriving from directions associated with known GNSS navigation sources. This technique is the most general and powerful for broad classes of RFI, but requires a more sophisticated antenna with a substantial (TBD) cost impact to the user.

Other innovations may be applicable, and may be developed in the future.

Appendix D

MES/GLONASS LINK MARGIN ASSESSMENT
(last update: 6/11/94)

Assumptions:

1. MES channels are on 1.23 MHz centers starting at 1610.865 MHz
2. MES out-of-band emissions are characterized by IM skirt and broadband noise
3. GLONASS channels are on 562.5 kHz centers; Chnl 0 is 1602 MHz
4. A GLONASS receive channel will effectively filter the MES spectrum with a squared $\sin(x)/x$ filter characteristic whose null-to-null passband = 1.022 MHz

$i := 1, 2 \dots 13$ Index for Globalstar channels

$j := -6, -5 \dots 24$ Index for GLONASS channels

$MES_freq_i := 1610.865 + 1.23 \cdot (i - 1)$ Subscript is from 1 to 13

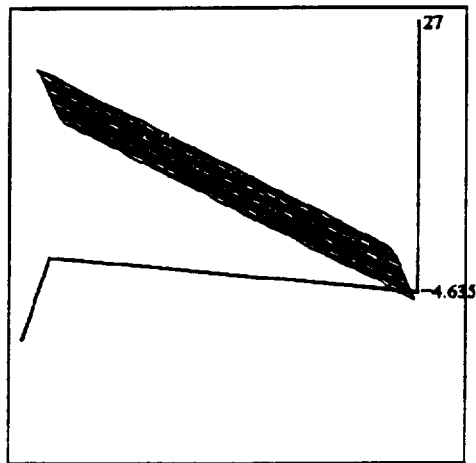
$GLON_freq_{j+7} := 1602 + 0.5625 \cdot j$ Subscript is from 1 to 31; chnls from -6 to 24

$Freq_offset_{i,(j+7)} := MES_freq_i - GLON_freq_{j+7}$

$Freq_offset_{1,1} = 12.24$

Define MES emission spectrum (dBW/MHz)

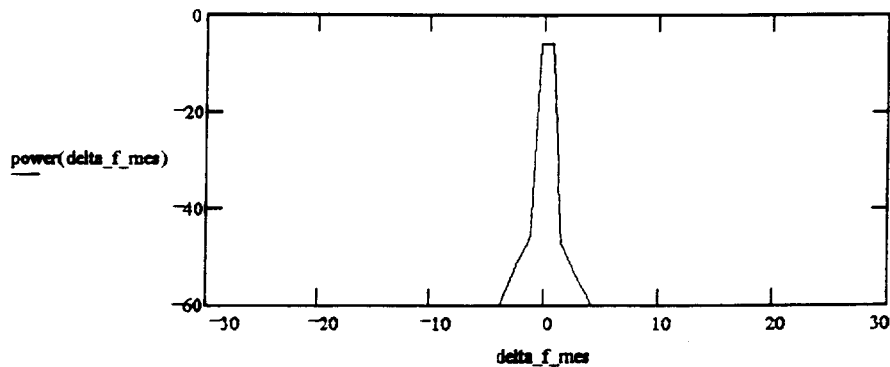
$freqs := \begin{bmatrix} -35 \\ -4 \\ -0.615 \\ -0.614 \\ 0.614 \\ 0.615 \\ 4 \\ 35 \end{bmatrix}$	$powers := \begin{bmatrix} -60 \\ -60 \\ -43 \\ -6 \\ -6 \\ -43 \\ -60 \\ -60 \end{bmatrix}$
-----------------------------------------------------------------------------------------------------	----------------------------------------------------------------------------------------------



$Freq_offset$

$\delta f_mes := -30, -29.1 \dots 30$

$power(\delta f_mes) := \text{interp}(freqs, powers, \delta f_mes)$



Calculate equivalent RFI signal power in a GLONASS channel

$$f_{lo,i,(j+7)} := \text{Freq_offset}_{i,(j+7)} - 1.22$$

$$f_{hi,i,(j+7)} := \text{Freq_offset}_{i,(j+7)} + 1.22 \quad \text{Integrate to second null}$$

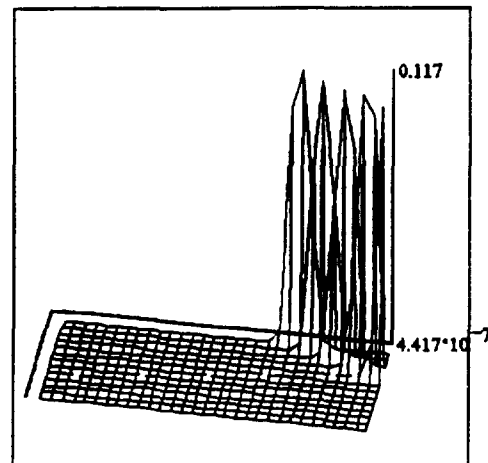
$$\text{Power_rfi}_{i,(j+7)} := \int_{f_{lo,i,(j+7)}}^{f_{hi,i,(j+7)}} \left[\frac{\sin \left[\pi \frac{f - \text{Freq_offset}_{i,(j+7)}}{0.511} \right]}{\left[\pi \frac{f - \text{Freq_offset}_{i,(j+7)}}{0.511} \right]} \right]^2 \cdot 10^{\frac{\text{interp}(\text{freqs}, \text{powers}, f)}{10}} df$$

$$\text{Power_rfi_db} := (10 \cdot \log(\text{Power_rfi}))$$

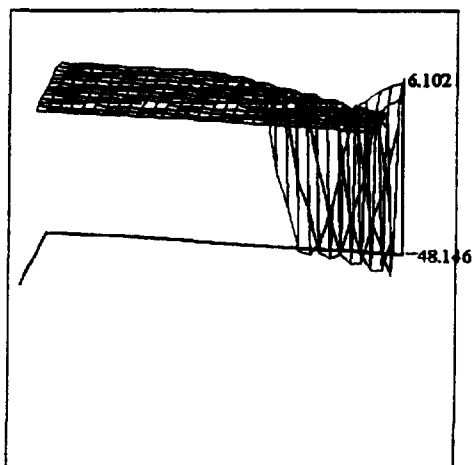
$$\text{Margin_db} := (-57.447 - \text{Power_rfi_db})$$

$$\text{Sigma_db} := \frac{\text{Margin_db} + 5.8}{3.7}$$

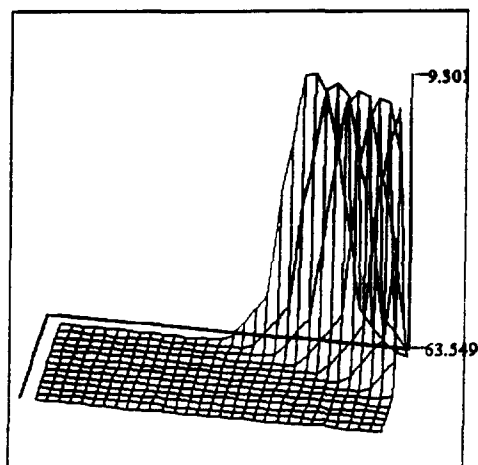
$$\text{Prob_exceed} := (1 - \text{cnorm}(\text{Sigma_db}))$$



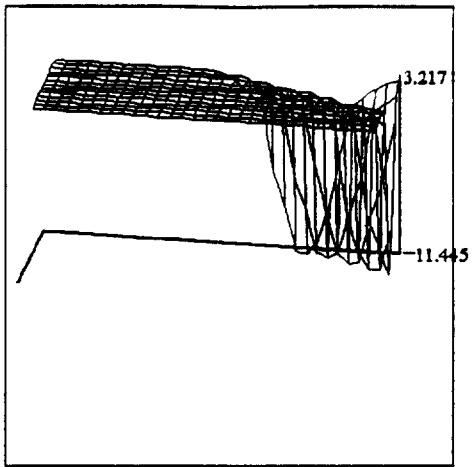
Power_rfi



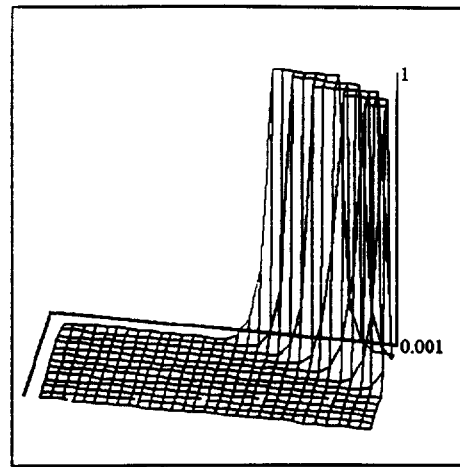
Margin_db



Power_rfi_db



Σ_{db}



Prob_exceed

